Techno-economic viability of integrating satellite communication in 4G networks to bridge the broadband digital divide

***Abstract*— Bridging the broadband digital divide between urban and rural areas in Europe is one of the main targets of the Digital Agenda for Europe. Though many technological options are proposed in literature, satellite communication has been identified as the only possible solution for the most rural areas, due to its global coverage. However, deploying an end-to-end satellite solution might, in some cases, not be cost-effective. The aim of this study is to give insights into the economic effectiveness of integrating satellite communications into 4G networks in order to connect the most rural areas (also referred to as white areas) in Europe. To this end, this paper proposes a converged solution that combines satellite communication as a backhaul network with 4G as a fronthaul network to bring enhanced broadband connectivity to European rural areas, along with a techno-economic model to analyze the economic viability of this integration. The model is based on a Total Cost of Ownership (TCO) model for 5 years, taking into account both capital and operational expenditures, and aims to calculate the TCO as well as the Average Cost Per User (ACPU) for the studied scenarios. We evaluate the suggested model by simulating a hypothetical use case for two scenarios. The first scenario is based on a radio access network connecting to the 4G core network via a satellite link. Results for this scenario show high operational costs. In order to reduce these costs, we propose a second scenario, consisting of caching the popular content on the edge to reduce the traffic carried over the satellite link. This scenario demonstrates a significant operational cost decrease (more than 60%), which also means a significant ACPU decrease. We evaluate the robustness of the results by simulating for a range of population densities, hereby also providing an indication of the economic viability of our proposed solution across a wider range of areas.**

Keywords*— *Techno-economics, broadband digital divide, satellite, 4G

I. Introduction

While the ICT revolution continues at a fast pace bringing new technologies such as Internet of Things (IoT), machine learning and block chain, half of the people on earth are still without a fast and reliable Internet connection. However, broadband Internet is no longer seen as a comfort, but as a basic service: "Like electricity a century ago, broadband is a foundation for economic growth, job creation, global competitiveness, and a better way of life" (FCC, 2010). The disconnected users are mostly located in rural areas. In (Townsend et al., 2013), broadband connectivity is seen as the essential protector against the depopulation of these rural areas, thanks to the wide range of available services such as public e-services, e-learning, telemedicine and online social networking.

From a policy perspective, providing high-speed broadband connectivity for rural users is one of the main challenges facing the European countries to satisfy targets announced in the Digital Agenda for Europe (Polykalas et al., 2017). Therefore, the public-policy focus on the digital divide is shifting towards broadband Internet access. In Europe, only 53% of rural homes are covered by next generation access compared to 80% of overall EU households (European Commission, 2018).

Based on (ITU report, 2015), important global reasons for not having broadband Internet access are[1]:

a) Internet service is not available;

b) Internet service is available but does not correspond to household needs;

c) Cost of service is too high.

It is clear that when it comes to bridging the broadband digital divide, one should look at both technical and economic parameters. Many technical solutions have been proposed to tackle the absence of broadband infrastructure. A full wireless-based solution with the combination of WIMAX and Wi-Fi technologies was proposed by Lo et al. (2012). This paper investigates the use of WIMAX to provide backhauling support, while Wi-Fi is used to provide access to the end user. This solution cannot provide global coverage of the areas under study as Wi-Fi access points are only installed where houses are clustered. In another study, a fiber-based solution was developed to connect rural areas in India (Dalela et al., 2014). Using a geo-intelligent algorithm authors aim to identify the optimized GPON tree to reach rural areas from the nearest provider's central office. The algorithm considers the terrain constraints such as difficult hilly terrain, deserts, and coastal regions, and demonstrates an incremental fiber saving compared to the anticipated planning approach of 25.6% to 80%, depending on the terrain characteristics, but is still expensive. Dean Segel (2009) proposed to use a satellite network to augment or substitute the

[1] Note that the ITU mentions four reasons in total, the fourth being: knowledge or skills needed to use the Internet are lacking. This has been addressed by several papers (Preston et al., 2007), (Abrardi & Cambini, 2019), and (Moghaddam et al., 2013), but will not be tackled in this paper.

terrestrial connection in rural areas with limited connection. A hybrid-terrestrial solution was proposed where the communication unit is QoS aware, allowing to forward traffic over different backhauling systems depending upon the latency-sensitivity of the traffic. Within the same technology, i.e. satellite, Liolis et al. (2019) have identified several use cases of integrating satellite into 5G networks. One of these use cases deploys satellite as a backhaul network to reach unserved rural areas, while 5G will be deployed as an access network.
Though relevant from a technological perspective, the studies mentioned above only focus on bringing broadband connectivity to the unserved/underserved areas without taking into account the cost of the service, the third cause of not having broadband access.

A variety of studies address both the lack of the network infrastructure and the cost of the broadband service. Van der Wee et al. (2014), for example, applied a cost-benefit model on specific scenarios, which are different in term of area type, demand uptake, and revenue scheme. Results prove that deploying a FTTH is only viable in a dense urban area with an aggressive take-up. Frías et al. (2015) introduced a cost model to compare a fixed broadband network (FTTH) with a wireless one (LTE) and applied it to rural Spain. Furthermore, a techno-economic modelling method for choosing the adequate rural broadband access solution was proposed by Krizanovic Cik, V et al. (2016). A second techno-economic model that applies geo-based multi-objective optimization to find areas with the highest concentration of unserved/underserved users in the USA at the lowest cost to service providers was developed by Durairajan et al. (2017). A converged optical-wireless architecture for interconnecting rural areas in Europe proposed by Polykalas et al. (2017), was consolidated by a techno-economic study for connecting the rural areas and islands complex in Greece. This study proved that, only by using 30% of public funding and 30 % of cost sharing (i.e. infrastructure sharing between telco and grid operator), the entire Greek islands complex can be covered by a high-speed fixed-mobile network. Recently, Ioannou et al. (2018) carried a comparative techno-economic study between FTTdp (Fiber To The distribution point) and LTE networks in order to estimate the needed ARPU for rural Greece, finding that both solutions are too expensive for the citizens of rural areas (ARPU for FTTdp is 332 euro and for LTE is 66 euro for 30 Mbps download speed). On a larger scale, Feijóo et al. (2018,) used a techno-economic framework to calculate the needed total investments to fill the broadband gap for urban, suburban and rural geo-types in EU-28. This framework proved first, that in term of broadband investment, the main gaps are occurring in rural areas, and second that around 50 billion euro is needed to bridge these gaps. Though relevant, these models did not look at the willingness to pay of the end user. We should bear in mind that in most rural areas, inhabitants have a lower income and the price of the service is crucial for its adoption.

From the discussed literature, we can deduct that rural areas are still underserved and that, while technological solutions exist, they frequently are too expensive for market players to invest in. This paper therefore combines technical aspects with techno-economic evaluation that takes into account Willingness to Pay, in order to propose a viable solution for connecting remote rural areas, specifically the European white areas. The proposed solution is a hybrid satellite-wireless solution in which a geostationary satellite (GEO satellite) network is to be deployed as a backhaul network. The GEO satellite is chosen thanks to its global coverage and high capacity. For the access network (fronthaul), we select the 4G technology, as it is not only one of the Next Generation Network (NGN) technologies but also provides up to approximately 100 Mbps as a peak data rate. In order to evaluate the economic viability of the proposed solution we use a Total Cost of Ownership (TCO) model and compare the Average Cost Per User (ACPU) to the Willingness To Pay (WTP) of the end users derived from desk research.

The article proceeds by presenting the actual conditions of broadband connectivity in Europe in section II. In section III, the proposed converged satellite-4G solution is presented. Section 0 highlights the cost model, a simulation of the model based on a hypothetical use case is presented in section V. Section VI evaluates the robustness of the results by simulating for a range of population densities and by assessing the impact of the caching data rate. The last section, section VII, summarizes the results and discusses future work.

II. BROADBAND CONNECTIVITY IN EUROPE

There is no universal consensus on the minimum download and upload speeds for a service to be classified as a broadband. The European Commission mentions both 144 kbps and 3 Mbps, while the FCC (Federal Communication Commission) in the United States defines broadband at speeds of minimum 25 Mbps (Davies, 2016). However, a consensus exists on the key role that broadband access plays in job creation, social and digital inclusion, society's well-being and the economic growth. On the European level, there is a current debate on broadening the concept of the Universal Service Obligation (USO) to include broadband access (Davies, 2016), (Bohlin et al., 2010) and (Xavier, 2003).
The idea behind a USO is to ensure all citizens have the right to the same services independently of their location. In Europe, the universal service from a telecommunication perspective is outlined by the directive 2002/22/EC "Universal service and users' rights relating to electronic communications networks and services (Universal Service Directive)" (European Commission, 2002). In this Directive, the European Commission (EC) states that "The concept of universal service should evolve to reflect advances in technology, market developments and changes in user demand". To reflect this dynamicity, the EC states in the same directive (under Article 15) that the Universal Service Directive (USD) should be reviewed in the light of not only the technological development but also economic and social ones. Following this decision, the EC has reviewed the directive three times since 2005. The main points included in these three consultations are:

- In the 2005 consultation on broadening the scope of the Universal Service Directive (USD) to include broadband, the EC concluded that only a minority of the European citizens are using broadband services (e.g. penetration rates of around 25% in countries such as the Netherlands and Denmark (Picot & Wernick, 2007)). As a result of the low penetration rate, the criteria to include broadband services in the USO were not satisfied.

- The results of the 2010 consultation were different from the one of 2005 giving the significant increase of the broadband penetration (24% at EU 25 in 2009 compared to only 8% at EU 25 in 2004 (Eurostat, 2009)). However, the EC concluded that: "At this stage, it would not be appropriate to include mobility or mandate broadband at a specific data rate at EU level" (European Commission, 2011), mainly due to the huge investment required to ensure the availability and affordability of broadband to the whole Europe. On the other hand, in order to minimize the possible market distortion resulting from broadening the scope of USO, the EC advices Member States to use public intervention tools to guarantee broadband availability outside the framework of the USO.
- In the 2016 consultation, (European Commission, 2016b) and (Davies, 2016) estimated the cost of providing the primary basket (consisting of 9.6Mbps connectivity) by 2020 for all the EU citizens to be 13.7 billion Euro. In addition to that, the cost of the social tariffs of broadband (considered at the same level of social telephony tariffs) would be around 147 million Euro annually. The study concluded that the most efficient mechanism of financing the broadband universal service would be public funds. They argue this choice by the fact that the entire society would benefit from the availability of broadband on both the economic and social sides. Currently, the USF (Universal Service Funding) is financed by the telecommunication sectors together with public funds. Therefore, it seems unfair to provide broadband connectivity using USFs, because other stakeholders will also benefit from a wider broadband access like the online service providers etc…. Hence, other means of funding have to be investigated.

As a conclusion of these reviews on the scope of the universal service, the EC, Member States, telecommunication operators and all the broadband contributors agreed that broadband connections should be made available at an affordable price to all the EU citizens, however without including an exact minimum bitrate in the USO. Nevertheless, the EC still refers in its reports e.g. (European Commission, 2015), to areas served by less than 2 Mbps as areas without broadband services[2].

Therefore, the EC has set a clear policy towards the deployment of high-speed broadband giving its socio-economic benefits. In 2010, the EC announced the Digital Agenda for Europe (DAE) which consist of 3 main targets: (1) availability of broadband for all Europeans in 2013, (2) deployment of 30 Mbps broadband capability to all Europeans by 2020, and (3) adoption of 100 Mbps broadband by 50% of European households by 2020 (European Commission, 2013a). Following the announcement of the Digital Agenda for Europe 2020, the European Commission (EC) has adopted a new strategy towards its broadband program called "Connectivity for a European Gigabit Society 2025" in September 2016 (European Commission, 2016a). The main targets (for 2025) announced in this agenda were:

a) Provide gigabit connectivity for all of the main socio-economic drivers.

b) Guarantee an uninterrupted 5G coverage for all urban areas and major terrestrial transport paths.

c) Access to connectivity offering at least 100 Mbps for all European households.

The last ambitious target of this agenda aims to the global coverage of Europe by at least 100 Mbps before 2025. As mentioned above, the rural EU average coverage for NGA (Next Generation Access) technologies at 39.2%, continues to be significantly lower than the total NGA coverage (76.0%) (European Commission, 2018). However, as urban areas start to reach the saturation stage of NGA coverage, deployment should shift towards rural areas to bridge the gap. As mentioned before, billions of euro should be invested for deploying network infrastructure. The most important parts of these investments are foreseen to come from the private sector, especially from the broadband providers. However, the private sector considers the rural areas as a non-viable market because the cost of deploying a network outside the urban and suburban areas is on average 80 % higher (Schneir et al., 2016). Moreover, a study carried by the European investment bank showed that 41% of the entire broadband investment should be allocated to rural areas in order to offer high-speed broadband to all European citizens. A similar study by Point Topic even mentions 63% instead of 41% (Point Topic, 2013).

Therefore, the EC has encouraged Member States to use public financing in line with the European Union competition and State Aid rules to achieve the speed, coverage and growth targets of the Europe 2025 agenda. The EC has defined a set of conditions that should be satisfied in order to acquire subsidies for the broadband rollout. These conditions are built on the classification of areas into white, grey and black. White areas are where there currently is no broadband provider and unlikely to be in the near future; grey ones are areas where there is only one broadband provider and black areas are covered by more than one broadband provider (European Commission, 2013b). Hence, white and grey areas are the only eligible areas to receive the State Aid funding.

Several Member State proposals have been approved by the EC concerning the public funding of broadband deployment. More specifically, 60 proposals were approved during the last three years by the EC (European Commission, 2014), most of them detailed how they aim to deploy new broadband infrastructure while assuming the possible rate of the service demand.

However, there will still be a large need for private funds in reaching the target.

[2] In this paper, we consider basic or universal broadband services to have at least 2Mbps as download speed.

On the other hand, in order to reach the 100% coverage in rural areas, not only the network rollout and its cost should be considered but also the price of the service and the willingness to pay (WTP) by the end user, as the ability of the operators to invest is driven by the end-users' willingness to pay (Lemstra, 2016). Ovando, C. et al. (2015) proved that for rural areas only a very high take-up could make the deployment of broadband networks feasible, while the demand of broadband services is very sensitive to price based on the socio-economic specifications of those areas. Moreover, not only the price of the service can affect the adoption of broadband but also other factors such as the age of end users as proven in (LaRose, R. et al., 2012). Finally, Glass, V. et al. (2010) believe that marginal increases in speed do not attract customers anymore, but that the inclusion of new services such as video could lead to an increase in take-up and willingness to pay. It is exactly this diversification of services and the offering of new services such as video streaming, video gaming and virtual reality VR applications, that requires a high-speed broadband.

Recently, Liu et al. (2018) proposed a model to estimate the willingness to pay for broadband Internet speed in the United States. Results of this study reveals a concave households' valuation of the broadband bandwidth. For example, in order to increase the bandwidth from 4Mbps to 10Mbps, customers are willing to pay 2.34$ per Mbps (14$ in total). Yet, to increase the bandwidth from 100Mbps to 1Gbps they only willing to pay 0.2$ per Mbps (19$ in total). In addition to that, a noteworthy result found in this research is that costumers value a decrease in latency from 300-600 milliseconds to 10 milliseconds by around 8$/month, which is equivalent from moving from Internet over satellite service to 4G services (we will come to this later on this paper: section V.B). It is important to mention here that this data is coming from two surveys that took place in the United States. Therefore, extrapolating these results to the European level should take into account the difference in term of willingness to pay between the American and the European citizens, but at least, they give an order of magnitude of the correlation between the WTP and the broadband speed.

According to (European Commission, 2017), the average European price of a mobile broadband service at 2 Mbps speed (which results in 1.6 GB data per month assuming that users are active only 9 hours per day and consume in average 80% of the bandwidth) is between 23 to 31 euro per month. This price should be valid for both urban and rural areas. However, if we aim for a good service adoption, this price has to be decreased by 15% to be adopted by rural inhabitants as well as non-adopters in urban areas according to a wide survey carried out in the USA (Carare et al., 2015). We should hence account for an average WTP of 19 euro per month for a decent broadband connection in a rural area.

In the light of this literature overview, we can infer that solutions that optimize for both technical (broadband technology) and economic (demand and willingness to pay) requirements for network deployment in unserved areas are needed and, to the best of the authors' knowledge, not readily available in literature. In the next section, we present our solution that covers both requirements.

III. Converged Satellite-Wireless architecture for interconnecting rural areas

We propose a converged satellite-wireless solution that takes into account (1) the technical requirements of high-speed broadband and (2) the economic constraints, being the cost of the network deployment and the willingness to pay of the rural inhabitants. Therefore, we investigate in the first subsection (section A) the status of satellite broadband. In section B, similar proposed solutions in literature are discussed. We finalize this section by detailing the technical description of our solution.

A. Status of satellite broadband:

Using satellite for broadband connectivity has several advantages: it is the only readily available technology that has a worldwide coverage, while also being capable to provide high-speed capacity. For that reason, the EC has considered its first target of the DAE, which is 30Mbps broadband speed for all citizens by 2013 as achieved (European Commission, 2013a) relying on the global coverage of satellite.

However, according to (Point Topic, 2015) there are two main challenges facing the deployment of satellite solutions in rural areas:

1) The unawareness of the end user about the availability of the Internet satellite providers, which justify why broadband satellite in Europe has a market share below 1% compared to other technologies (Gómez et al., 2016). As a solution, the EC together with the satellite providers have developed an online tool (www.broadbandforall.eu) in order to establish a connection between users and the local satellite suppliers.

2) The insufficient political support for the satellite broadband. In fact, the State Aid documentation refers for the next generation solutions as wired or mobile solutions and satellite solutions have been marginalized. On the other hand, there is a general consensus among satellite operators that a 30 Mbps Service Level Agreement (SLA) cannot be achieved at any reasonable and affordable price without some intervention.

In fact, an end-to-end satellite solution may not be viable, for many reasons. First, the end users need to buy a satellite receiver (well known as VSAT) which is around 800 euro without counting the price of the installation (VSAT, 2018). In addition to that, the price of the broadband service itself is very expensive, about 99 euro for a volume of 2GB per month, with maximum speeds of only 10Mbps/2Mbps (download/upload) (VSAT, 2018). Giving that, we can think what the price for 30 Mbps would look like.

As a conclusion, satellite operators are not able to expand their networks to meet the goals of the EC agenda, given the present funding policies. On the other hand, the EC will not achieve the goal of 30Mbps coverage for all Europe without the help of satellite operators.

As a possible solution for this “dilemma”, we suggest in this paper to combine the 4G networks as fronthaul network with the satellite networks as a backhaul. The use of 4G networks aims to decrease the cost of the radio access network. In addition to that, satellite networks from a technical perspective are the most eligible to serve as a backhaul networks for rural areas given their advantages as presented above.

B. *State of the art of Satellite-4G network solutions:*

Section I introduced some papers that support the use of satellite as a backhaul network to serve rural areas (Dean Segel, 2009) and (Liolis et al., 2019). They motivate the choice of using satellite technology as a backhaul network by the expensive cost of upgrading the terrestrial backhaul route, which could cost millions of dollars, yet the potential new revenue cannot cover this cost.

From a technical perspective, several sources studied the compatibility between 4G and satellite networks (ETSI, 2002), (ITU report, 2010), (Siyang et al., 2013) and (Zangar et al., 2009). Some technical challenges generated by the combination of satellite and 4G networks have been addressed as well. Zangar et al. (2018) addressed in their work the “key challenge” in the 4G-Satellite integration which is the radio resource allocation policy. The main challenging aspect according to (Abdelsalam et al., 2017) in order to ensure the smooth combination of 4G and satellite networks is the management and the handling of the TCP connection. The same authors recently analysed the bandwidth aggregator techniques for hybrid satellite-xDSL links (Abdelsalam et al., 2018).

C. *Proposed Satellite-4G solution:*

This paper presents a solution that takes advantage of the satellite communication’s global coverage and uses it as a backhaul network. In addition, the solution relies on a 4G access network, as one of the NGA technologies, to be deployed as a fronthaul network. The proposed solution aims to provide broadband connectivity to white areas where there is no broadband provider and it is unlikely to be in the near future. However, in areas where there are already basic broadband services (but not NGN), satellite solutions can complement the existing terrestrial solution as described in (Liolis et al., 2019)., but this case is out of scope of this paper.

The complete network solution is composed of:

1. A 4G core network that treats and processes the offered services,
2. A satellite gateway connected to the 4G core network via a fiber connection, which is responsible for forwarding the traffic from the core network to the radio access network (RAN) via a satellite link,
3. A satellite terminal installed near the RAN that receives the traffic from the satellite gateway via the satellite link and sends it to the RAN and vice versa,
4. Finally, a RAN which consists of eNodeBs (evolved Node B, i.e. mobile base stations), responsible of carrying out the traffic from the 4G core to the end user and vice versa.

The network architecture is presented as follows:

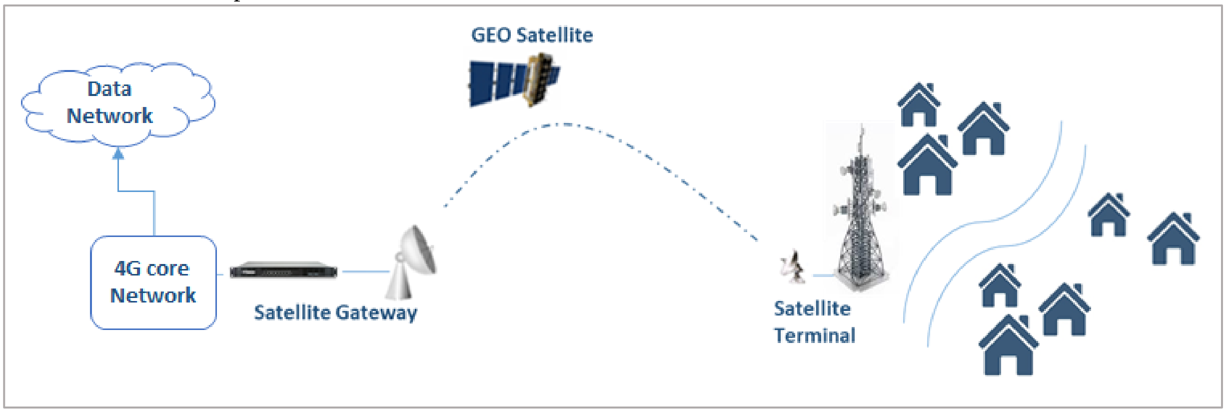


Figure 1 Network architecture of the integrated satellite-terrestrial solution

To study the viability of the integration of satellite communication within the 4G mobile network, a cost model is defined and discussed in the next section.IV

IV. COST MODEL

The proposed model takes into account both the Capital (CAPEX) and the Operational Expenditures (OPEX), designed for converged networks, and considers a planning horizon of 5 years. This model aims to calculate the Total Cost of Ownership (TCO) as well as the Average Revenue Per User (ACPU) for the studied scenario. This model aims to study the economic feasibility of the 4G-satellite solution in rural Europe. In section A, we will discuss in more detail the structure of the model. The mathematical formulation of the model is presented in section B.

A. Model structure

The main inputs of the model are the bill of materials (BOM), the number of users, the minimum bitrate per user, the average margin of profit of telecoms operators and the time horizon of the project. Those inputs feed into a cost model that consists of four sub-models in alignment with the network architecture components presented in the previous section. The first sub-model is designed for the edge site. It incorporates the CAPEX of the radio access network (RAN), the capex of the satellite terminal, the common capex and the OPEX of all edge components. The second one models the satellite network used for the backhaul; both CAPEX and OPEX are taken into account. The third block builds the model of the costs for the 4G core network and the last block in the diagram englobes all overhead costs. After the calculation of the CAPEX and OPEX for all these blocks, the TCO can be derived. Hence, given the TCO as well as the number of users, the ACPU can be derived as an output of the model. The structure of the model is presented in Figure 2.

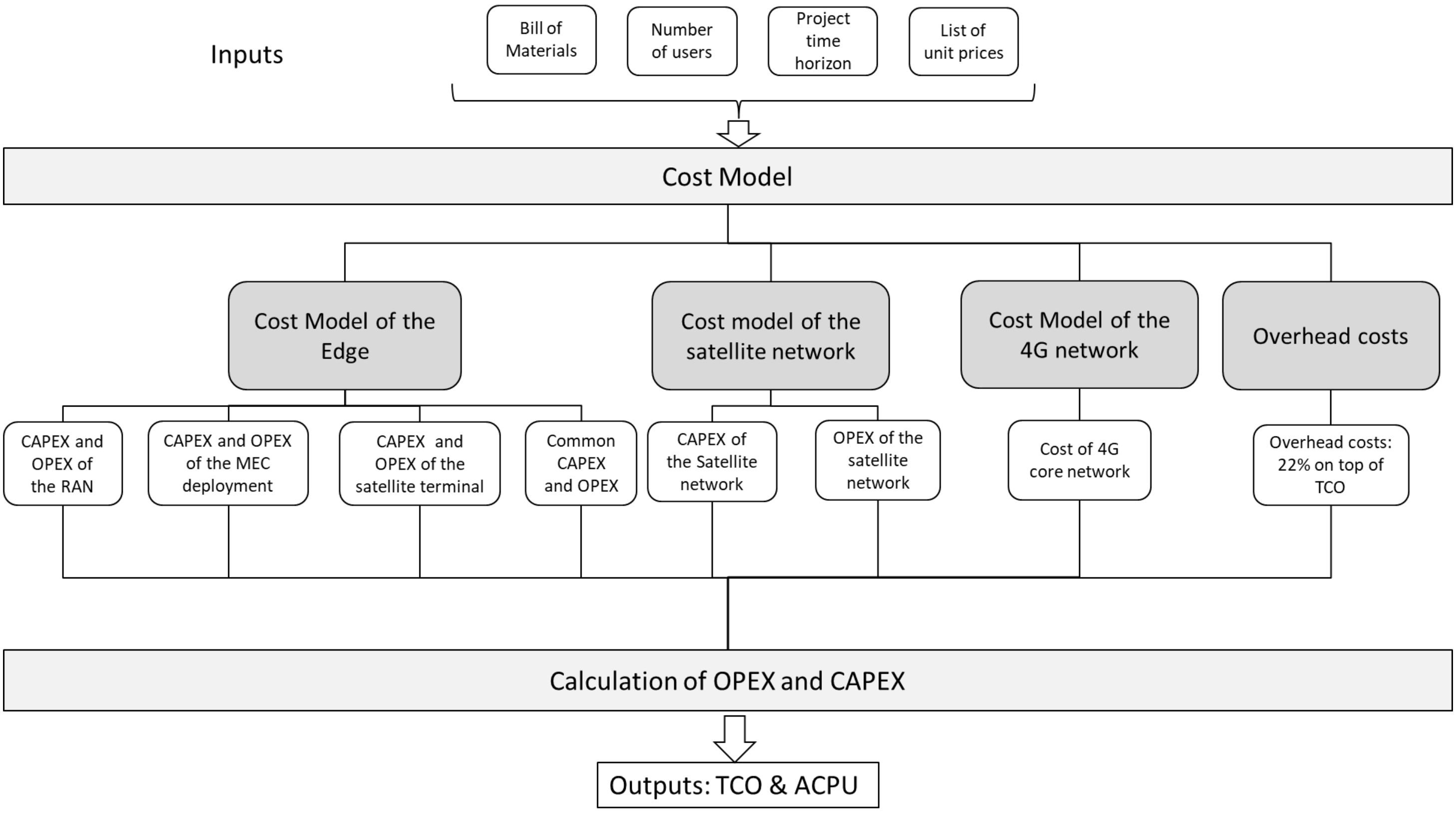


Figure 2 Cost model structure

B. Mathemathical formulation of the model

The previous section has presented, from a high-level perspective, the structure of the proposed cost model. In this section, we will detail each sub-model formula used to calculate both CAPEX and OPEX parts. An overview of abbreviations can be found in Table 1.

1) Cost model of the edge site

The cost of the edge incorporates the CAPEX of the RAN, the CAPEX of the satellite terminal, the common CAPEX and the OPEX of all the edge components. The number of equipment needed depends on the dimensioning process of the site, which in turn depends on the bitrate to be provided in the site $Br_s = N_u \times Br_u$ (Equation 1). The CAPEX of the RAN $Capex_{RAN} = N_{enb} \times C_{enb} + C_T + C_{Inst}$ (Equation 3) depends on the number of eNodeBs to be deployed, which is the maximum of the number calculated based on the bitrate and the coverage area of the served site $N_{enb} = MAX({Cov_a}/{Cov_{enb}}, {Br_s}/{Bw_{enb}})$ (Equation 2).

$$Br_s = N_u \times Br_u \quad \textit{(Equation 1)}$$

$$N_{enb} = MAX({Cov_a}/{Cov_{enb}}, {Br_s}/{Bw_{enb}}) \quad \textit{(Equation 2)}$$

$$Capex_{RAN} = N_{enb} \times C_{enb} + C_T + C_{Inst} \quad \textit{(Equation 3)}$$

$$Opex_{RAN} = Site_{rental} + (P_{eNBs} + P_{ST}) \times C_{watt} + M \quad \textit{(Equation 4)}$$

Furthermore, the CAPEX of the satellite terminal consists of the satellite terminal equipment, which is calculated based on its link capacity with the satellite. The common CAPEX incorporates all common capital costs needed to build the edge infrastructure. Finally, the OPEX of the edge $Opex_{RAN} = Site_{rental} + (P_{eNBs} + P_{ST}) \times C_{watt} + M$ (Equation 4) consists of the cost of the power consumption of all the equipment, the cost of the site rental per year and the maintenance costs.

2) Cost model of the satellite network

The cost model of the satellite network consists of two main parts. First, the CAPEX of the satellite gateway, which is the cost of the equipment and the building required to deploy the satellite gateway. Second the OPEX of the satellite network $Opexsat = C_{satCaps} + P_{satGat} \times C_{watt} + M$ (*Equation 6*), which is the cost of the satellite capacity $CsatCapS = (Br_S + Br_T) \times 12 \times C_{satMbps}$ (*Equation 5*), in addition to the cost of the maintenance and the power consumption.

$$C_{satCapS} = (Br_S + Br_T) \times 12 \times C_{satMbps} \quad \textit{(Equation 5)}$$

$$Opex_{sat} = C_{satCapS} + P_{satGat} \times C_{watt} + M \quad \textit{(Equation 6)}$$

3) Cost model of the 4G core network

For modelling the 4G core network, an estimation of the cost of the core network per user should be made. Given this estimation in addition to the number of users, the cost of the 4G core network can be calculated. This model uses results found by Bouras et al. (2016), which calculate the cost of 4G core network deployed to serve 100,000 users (corresponding to about 100 base stations).

4) Additional costs

We have built a realistic cost model using the following assumptions for the additional costs:

- Hardware installation cost is 15% of the hardware costs (Casier, 2010). The cost of the hardware installation is part of the CAPEX costs and it is expressed by the following formula:

$$C_{Inst} = 15\% \times C_{Hw} \quad \textit{(Equation 7)}$$

- Maintenance cost is 10 % of the CAPEX costs (Casier, 2010). Maintenance costs are counted in the OPEX costs.

$$M = 10\% \times CAPEX \quad \textit{(Equation 8)}$$

- In most cases, the overhead cost is defined as the cost of marketing, helpdesk, human resources, finance etc. According to (Atkearney, 2018) it is around 22% on top of the sum of the CAPEX and OPEX costs.

$$Ovhd_C = 22\% \times (CAPEX + OPEX) \quad \textit{(Equation 9)}$$

5) Total Cost of Ownership (TCO)

The Total Cost of Ownership (TCO) of the proposed solution is counted as the sum of the CAPEX, the OPEX of 5 years and the overhead costs of 5 years.

$$TCO = CAPEX + \sum_{t=1}^{5} OPEX(t) + Ovhd_c(t) \quad \textit{(Equation 10)}$$

Nomenclature	Designation	Nomenclature	Designation
Br_u	bitrate per user	H_u	average active hours per user
Br_S	bitrate per site	N_u	number of users
Cov_a	coverage area	$C_{satMbps}$	cost of 1 Mbps per month via satellite link
Cov_{enb}	eNB coverage	$C_{satCapS}$	cost of satellite capacity for a site S
Bw_{enb}	eNB bandwidth	Br_T	bitrate per site for traffic control and overhead
N_{enb}	number of eNB	M	maintenance costs
C_{enb}	cost of eNB	P_{satGat}	power consumption satellite gateway per year
C_T	cost of the tower	C_{watt}	cost of energy
N_s	number of servers	N_{stg}	number of storage
Mec_{mng}	cost of MEC software management	C_{stg}	cost of storage

C_s	cost of server	**N**	number of sites served by the satellite gateway
C_{Inst}	cost of hardware installation	**C_{Hw}**	cost of the hardware
$Ovhd_C$	overhead costs	**P_{eNBs}**	power consumption of the eNBs per year
$Site_{rental}$	Cost of renting the site for deploying the eNBs and the satellite terminal per year	**P_{ST}**	power consumption of the satellite terminals per year
$C_{satCapS\_Caching}$	cost of satellite capacity for a site S with caching data on the edge		

Table 1 Nomenclature

V. SIMULATION: HYPOTHETICAL USE CASE

To evaluate the proposed solution from a techno-economic point of view, we define a hypothetical use case, which will first be described. Inputs used to run the cost model are listed in the second section and finally results are analyzed in the third section.

A. Use case description

The case consists of a satellite backhaul connected to a cell tower located in a rural area in the EU covering two villages about 5km apart connected via a rural main road. The villages are home to 350 families, with an average of 3 users per home. The predominant traffic on the cell is eMBB (enhanced Mobile Broadband).

From the mathematical formulation of the model presented previously in section IV.B, we can conclude that the number of users as well as the minimum bitrate required per user are the main cost drivers of our model. First, they affect the dimensioning process; see $Br_S = N_u \times Br_u$ (Equation 1) and $N_{enb} = MAX({Cov_a}/{Cov_{enb}}, {Br_S}/{Bw_{enb}})$ (Equation 2). In addition, the OPEX costs $C_{satCapS} = (Br_S + Br_T) \times 12 \times C_{satMbps}$ (Equation 5) are directly driven by the bitrate per site.

In order to generate realistic results taking into account the bitrate per user cost driver, there are two ways to proceed. The first one is to forecast the average consumed mobile data traffic per user (i.e. monthly download volume) in the considered timeframe (2020-2024) and then calculate the bitrate per user that generates this amount of mobile data traffic. The second option is to set an initial bitrate per user according to the DAE 2020 target, namely 30 Mbps. We can assume that the first case corresponds to a conservative scenario and the second one to an aggressive scenario, and hereafter their description:

1) Conservative scenario

In order to have an idea about the future mobile data traffic, we refer to the well-known Cisco VNI report (Cisco, 2017). It forecasts that in 2022, the monthly mobile data traffic for Western Europe will be 8.8GB per user. To know the user bitrate needed to generate this amount of data we rely on Analysis Mason data used in the BATS project report (BATS, 2016). The calculation takes into account the number of hours during which the user is active, then it results that each 1GB per month corresponds to an average busy hour data rate of 7.8 kbps. Hence, 8.8 GB per month results in 68.64 kbps per user as an average busy hour data rate. However, this bitrate does not meet the definition of the broadband speed set by the EC. Thus, we consider the minimal speed in this scenario the one of the universal broadband service, being 2 Mbps. Hence, in this scenario we assume that the bitrate per user (3 users per family, 350 families) is 2 Mbps, thus taking into account the active user rate of 80% and the number of active hours of 9 per day, the resulted average busy hour data rate is 630 Mbps per site.

2) Aggressive scenario

In order to guarantee a good Quality of Experience (QoE) for the end user, the EC requires a bitrate of 30 Mbps per user for high-speed broadband services, as explained above. Hence, in this scenario we assume that the bitrate per user (3 users per family, 350 families) is 30 Mbps, thus taking into account the active user rate of 80% and the number of active hours of 9 per day, the resulted average busy hour data rate is 9450 Mbps per site.

For all the defined scenarios, on top of the site bitrate, we expect 10% traffic and control plane overheads.

B. Model inputs

Inputs used to run the cost model are presented in the following tables. General inputs of the model are described in Table 2. Parameters used for modelling the edge site, which consists of two parts: the RAN and the satellite terminal, as well as the satellite network and the 4G core network are presented in Table 3.

- **General inputs**

Parameter	Conservative scenario	Aggressive scenario
Study period	5 years (2020-2024)[3]	

[3] Use case definition

Area	78.5 km^2	
Average busy hour data rate per site	630 Mbps	9450 Mbps
Average active hours per user	9 [4]	
Active user rate (%)	80 [2]	
Cost of 1 kWh (€)	0.114 (Eurostat, 2017)	
Conversion rate ($ to €)	0.9	
Time Value of Money	5%	

Table 2 General inputs

- **Network inputs**

Parameter	Value
Edge inputs	
RAN	
Macro cell: 3 antennas, 1BBU, Software upgrades and maintenance	25-30K €
Macro cell bitrate	Maximal deployment is 5 * 3 sectors per eNB, (5*3*140= 840Mbps) (SAT5G, 2017).
building, rigging and materials (tower 10m)	10k $ (ESA, 2016).
Power consumption	18 144 kWh per year (SAT5G, 2017).
Satellite terminal (ST)	
Cost of ST	4K $ (Gilat, 2015).
Capacity of the satellite link/ST (Mbps)	150 (Gilat, 2015).
Satellite terminal power consumption	438 kWh per year
Air conditioning	~500 € (Airconco, 2018).
Common power consumption: cooling etc...	30835 kWh per year
Edge maintenance	10% of CAPEX (Casier, 2010).
Satellite Network inputs	
Satellite capacity cost ($/Mbps/month)	15-7 (2020-2025) (ESA, 2016).
Satellite gateway infrastructure (€)	Cost of satellite gateway is included in the cost of satellite capacity
Maintenance	10% of CAPEX (Casier, 2010).
4G core network inputs	
Cost of 4G core network (€)	2200K: deployed to serve 100 BS and each BS serve 1000 users (Bouras, 2016).
Cost of 4G core per user (€)	22

[4] These assumptions are derived based on Internet research, so may be realistic but not precise.

Table 3 Network inputs

C. Results and interpretation

1) Results for the baseline scenario

As a first step, we simulate the proposed architecture for the scenarios discussed previously: the conservative and the aggressive scenario, based on collected inputs presented above and assumptions discussed in section IV.B.
Results of the TCO for the three defined scenarios are presented in Figure 3.

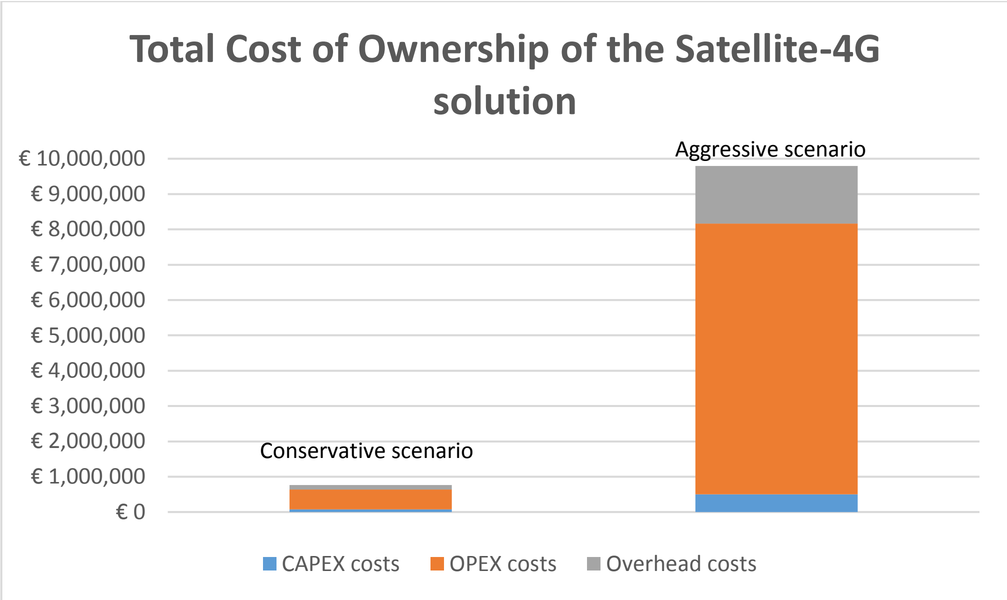


Figure 3 Comparison of the Total Cost of Ownership for the considered scenarios

The monthly ACPU for the conservative and aggressive scenarios can as such be derived: 12 and 155 euro respectively. The ACPU for the aggressive scenario (2Mbps) is not expensive comparing to the willingness to pay of the rural inhabitants (19 euro as discussed in section 0). Hence, the satellite-4G solution is viable for rural areas with a modest bitrate per user. However, if we opt for a good QoE (i.e. the aggressive scenario), the ACPU results in 155.56 euro, which is way higher than the WTP (especially if we take into account that the ACPU calculated here does not yet include a profit margin for the telecom operators or service providers).
In the view of optimizing these results, we examine the resulted cost components in more detail, we find that the OPEX are very high, as clearly observed in Figure 3. This is due to the satellite capacity (backhaul) that should be paid monthly. One of the solutions proposed to decrease these OPEX is to cache a percentage of the popular content on the edge and by doing so we decrease the amount of traffic that needs to be carried out via satellite link, in turn decreasing the operational costs (Wang et al., 2014).

2) Simulation with caching data on the edge to decrease OPEX

A. Caching technology

Tremendous growth of the video content request is foreseen for the next years. According to the Cisco VNI Forecast Highlights Tool, Internet video traffic will be 80% of all consumer Internet traffic by 2022 comparing to 73% in 2017, which corresponds to 29.5 EB (Exabyte) per month by 2022 compared to only 8.9 EB per month in 2017 (Cisco, 2019). This growth is driven by the expansion of VoD (Video on Demand) libraries. According to the same forecasting tool, consumer IP VoD traffic will reach 3.8 EB per month by 2022, yet, it was only 2.6 EB per month in 2017.
The traditional centralized networks cannot mitigate this exponential growth of user demand giving the heavy load on the backhaul links and the long latency (Wang et al., 2017). In order to accommodate the huge bandwidth requirements resulting from the massive demand of the high-definition video content, new network architectures based on caching strategies have been proposed. Essentially, caching techniques aim to store a duplicated copy of the most popular content in the network edge. In this way, the end user does not have to download it from a central location in the network. Hence caching techniques transform the bandwidth requirement into a storage requirement (Borst et al., 2010). Several papers in literature optimize content caching techniques and algorithms (Wang et al., 2014), (Wang et al., 2017) and (Rossini G. &. R., 2012).
The main question that should be addressed when a caching-based solution is chosen, is how much data we have to store in the edge. Cha et al (2009) proved that the Pareto law is valid for video content consumption in Internet. They found that 10% of the most popular videos on YouTube account for approximately 80% of the views. On the other hand, the 90% of the remaining video content has only 20% of views (the same results were found for Daum (a video service in Korea) as well).

B. *Caching scenario specifications*

Two reasons are behind the use of the caching technology in this scenario. The first one is to decrease the amount of the traffic that needs to be sent via satellite link, and by doing so, decrease the cost of the satellite capacity and hence the OPEX. Furthermore, caching popular content on the edge will not only solve the issue of increasing demand for bandwidth, but will also decrease the latency of the video traffic, as the content is placed closer to the end users. Therefore, our second reason is to decrease the latency for VOD service, and as discussed previously in section II, costumers significantly value the decrease of latency.

In the network architecture presented in Figure 1, we need to add Multi Edge Computing (MEC) infrastructure on the edge site (Hu et al., 2015). The role of the MEC is to cache a percentage of the popular content locally on storages on the edge and to communicate with the base station to receive users' requests and send back the corresponding content. An intelligent algorithm is there to update the cached data according to the frequency of usage and downloads of new content. We assume that the Pareto law is applicable here (as argued in the previous section). Hence 20% of popular content will be stored and 80% of user video requests are served from cached data. Therefore, 80% of the user's traffic is video (as argued previously in section V.A), and 80% of the video requests can be served from the cached data (which is 20% of the popular content), resulting in 64% of the user traffic to be served from the local cache. As this assumption directly affects the OPEX, a sensitivity analysis on the caching rate is given in section VI. The new network architecture is presented in the following figure:

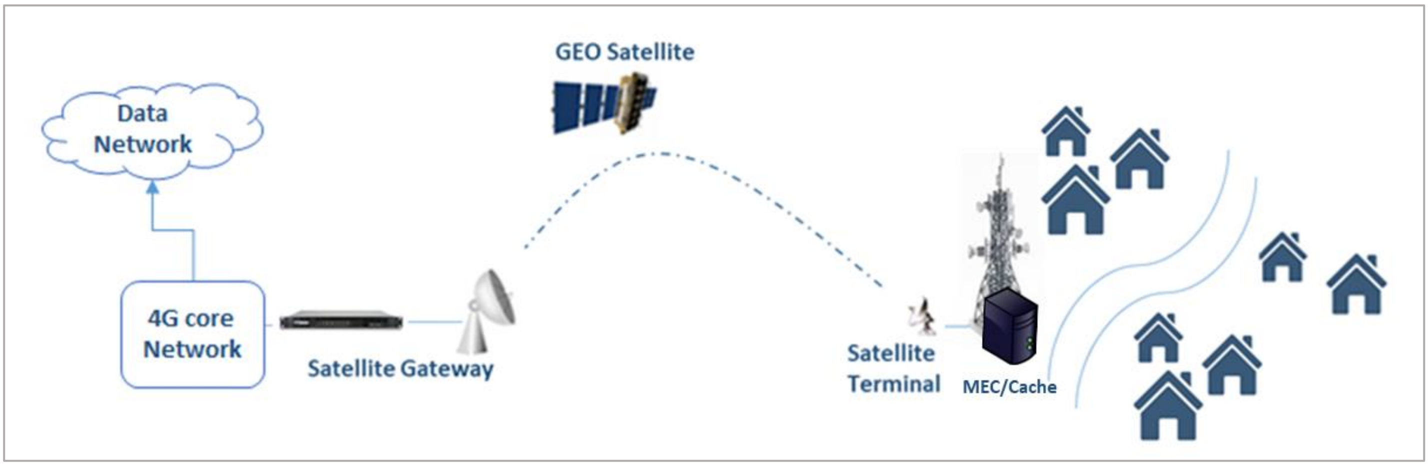


Figure 4 Network architecture of the proposed solution with the MEC deployment

In addition to changes in the network architecture of the proposed solution, there are also changes in the cost model structure (Figure 2). We need to take into account in the new model both the CAPEX and OPEX of the MEC deployment. Based on how much data can be cached on the edge, the number of storage equipment and servers required is calculated, and then the cost of the entire MEC infrastructure is derived based on the following equations:

$$Cost_{MEC} = CAPEX_{MEC} + OPEX_{MEC} \quad \textit{(Equation 11)}$$

$$CAPEX_{MEC} = N_S \times C_S + N_{stg} \times C_{stg} + \frac{Mec_{mng}}{N} \quad \textit{(Equation 12)}$$

The main difference between the two scenarios (without and with caching data on the edge) is the cost of the satellite capacity. Based on the number of user requests that will be served from the cached data R_{cd}, $Opex_{RAN} = Site_{rental} + (P_{eNBs} + P_{ST}) \times C_{watt} + M$ (Equation 4) becomes the following equation:

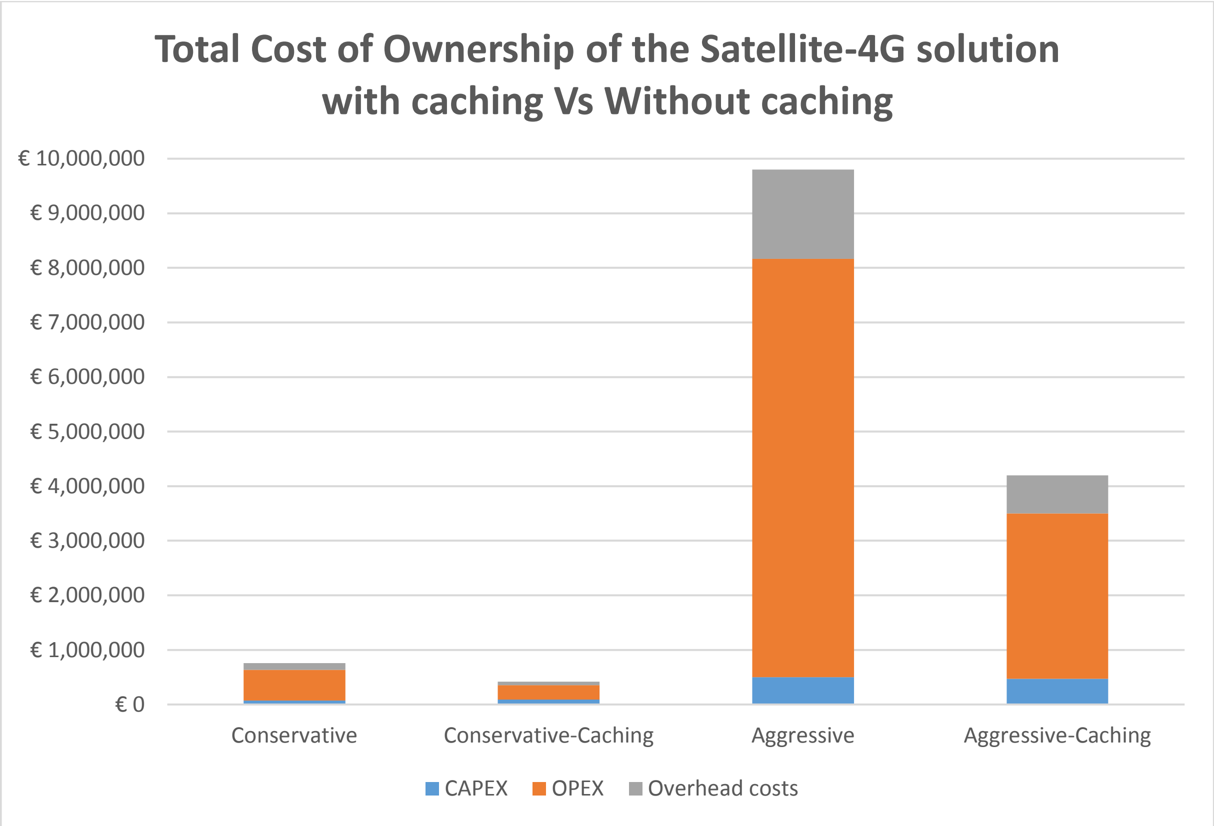
$$C_{satCapS} = ((1 - R_{cd})Br_S + Br_T) \times 12 \times C_{satMbps} \quad \textit{(Equation 13)}$$

The

Parameter	Value
Data	20%
Popular	YouTube
MEC (Lenovo, • Server	~700€

• TruDDR4 memory: 64 GB of RAM • Physical storage: 10 TB of SAS disks on 14 disks • 8 vCPU at 2Ghz • License cost	~800€ 2800€ 12k€
Management • 8 vCPU at 2,6Ghz, • 32 GB of RAM, • 600 GB of disk, with the license	60
MEC	3022.2

Table
When



Figure

ACPU	Conservative	Aggressive
Satellite-	12.1	155.6
Satellite-	6.7	66.6
ACPU	44.6	57.2

Table
From

- The ACPU reduction rate resulting from the use of the caching technology is more than 55% (for the aggressive scenario).

- The ACPU reduction rate increases when the bitrate required per site increases, this is explained by the fact that the bigger data rates we offer, the more requests are served from the cached data.
- The ACPU for the conservative scenario without caching is economically viable (compared to the WTP discussed previously). Yet the ACPU for this scenario with the use of caching concept is very cheap. Still, one needs to take into account the conversion of ACPU to actual ARPU (prices), using profit margins for the telecom operator and service providers.
- The deployment of the solution without using the caching concept is not cost-effective in the case of the aggressive scenario.
- A good speed thus a good QoE can be offered to the inhabitants of white areas thanks to the satellite-4G solution, in case a caching of the popular content is deployed in the edge.

These
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VI. SENSITIVITY ANALYSIS

In
The

Input	Distribution	range	Simulated	Related
Population	Uniform	13-	Conservative	REF _Ref529792103 \h * $Brs = Nu \times Bru$ (Equation 1
Caching	Uniform	0%-	Aggressive	$CsatCapS = ((1 - R_{cd})Br_S + Br_T) \times 12 \times C_{satMbps}$ (Equation 13

Table 6 Input variables for sensitivity analysis

A. *Impact of the population density on the result:*

In this section, we study the variation of the ACPU with and without caching data on the edge for the conservative scenario (as an output) according to the variation of the population density per km^2 (as an input). Results of this simulation are presented in Figure 6:

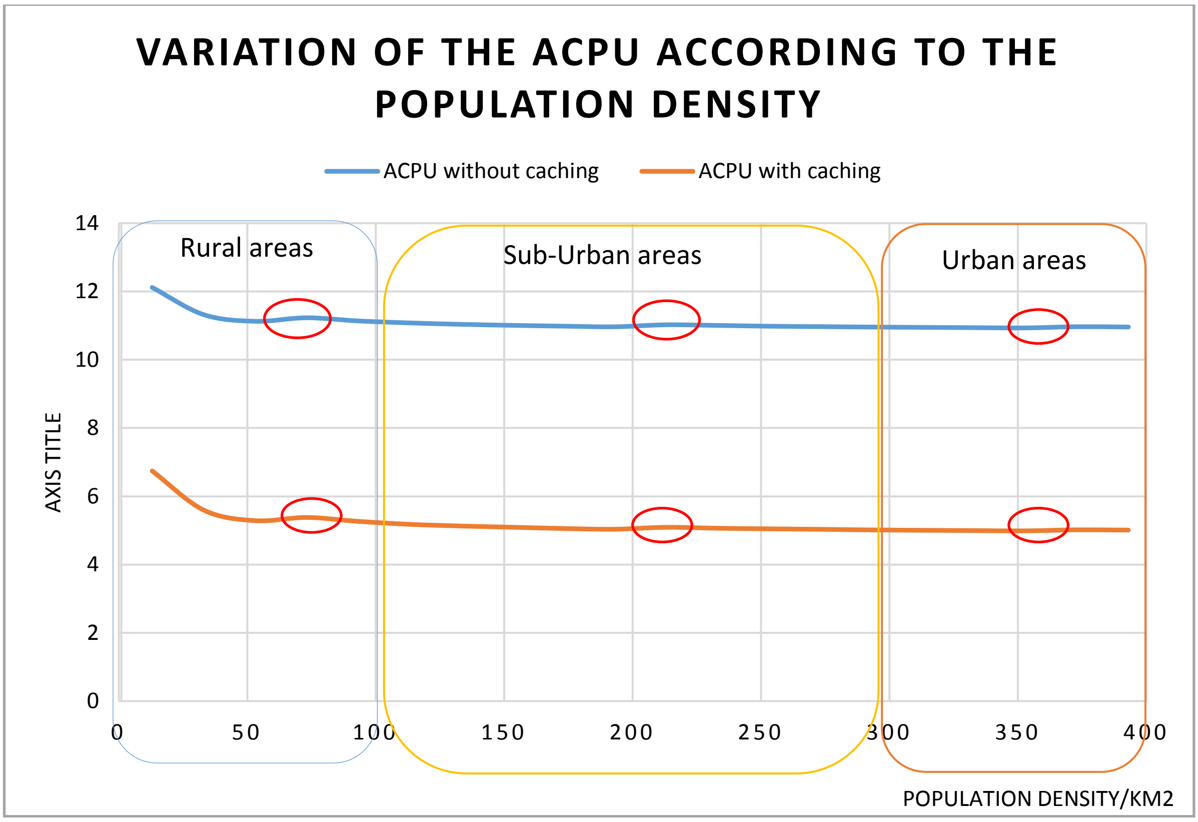

Figure 6 Variation of the ACPU for the conservative scenario according to the variation of the population

Based on the European criteria of the classification of regions (Eurostat, 2018), we classified in the figure above three main regions based on the population density. Rural areas presented with the blue rectangle (density under 100 inhabitants per km^2), sub-urban areas presented with the yellow rectangle (density between 100 and 300 inhabitants per km^2) and urban areas presented in the orange rectangle (density over 300 inhabitants per km^2). Several deductions can be extracted from the results of this simulation:

- A significant drop of the ACPU is seen in rural areas comparing to a slight decrease in sub-urban and urban areas. This is due to the non-need of adding new base stations within a specific margin of population density. For example, moving from the density of 13 inhabitants per km^2 to 26 does not require the installation of new base station which means the same cost of the infrastructure will be divided by the double number of users.
- A saturation point is reached starting from the population density of 200 inhabitants per km^2. This is because increasing the number of users extensively induces the increase of the required data rate per site thus increasing the number of base stations and satellite terminals that should be installed.
- Transition points between different densities with high ACPU can be observed in Figure 6, indicated with red circles. This high ACPU is due to the need to deploy new base stations to satisfy the additional bandwidth requirement, yet the number of users are not enough to cover this additional cost (the cost of the new installed base station).
- Similar to other broadband solutions, the cost per user of deploying the satellite-4G solution in urban areas is much cheaper than in rural areas.

The low cost of the proposed solution in sub-urban and urban areas can give insights to the operators about the suitable use of a similar solution to improve their services at a low cost. Two use cases for both the sub-urban and urban areas might be of interest.
The first use case for sub-urban areas consists on the consolidation of the "poor" terrestrial connection with the satellite connection to improve the speed and thus the QoE. This use case is mainly relevant to homes and small office home office (SOHO) premises located in underserved areas of developed countries, which are served with terrestrial telecommunication network infrastructure (xDSL or cellular access) of poor bandwidth performance (e.g., users are located far from the DSLAM or far from the 4G cell tower). In such underserved areas of developed countries, the use of satellite to complement the existing terrestrial broadband access link can lead to a hybrid satellite/terrestrial multi-play scenario, which can be envisaged in order to benefit from low-latency of terrestrial networks and high-bandwidth of satellite networks (Liolis et al., 2019).
The second use case concerns the use of the satellite solution in urban areas. This use case involves the delivery and offload of content (multimedia, network software updates etc.) in the mobile network via satellite alone or a combination of satellite and terrestrial links for local caching. Onward delivery is by fetching from the cache and has the advantage of lower latency and

potential improved QoE. Satellites are well suited to provide such broadcast/multicast resources over wide areas to aggregate the largest audience possible and hence to reduce the global delivery cost. Combining satellite broadcast/multicast resources with the terrestrial unicast resources is a powerful way to optimize the content delivery costs and improve scalability (Liolis et al., 2019). The feasibility of these two uses cases from a techno-economic point of view is out of scope of this paper, but can be tackled in future studies.

B. Impact of the caching rate on the result:

We argued previously the assumption on the caching rate in section V.B. However, this assumption has a big impact on the results, as can be seen from the mathematical formulation of the model (section IV.B). To this end, we study in this section the variation of the CAPEX and OPEX in function of the caching rate. Results of this simulation in presented in the figure below:

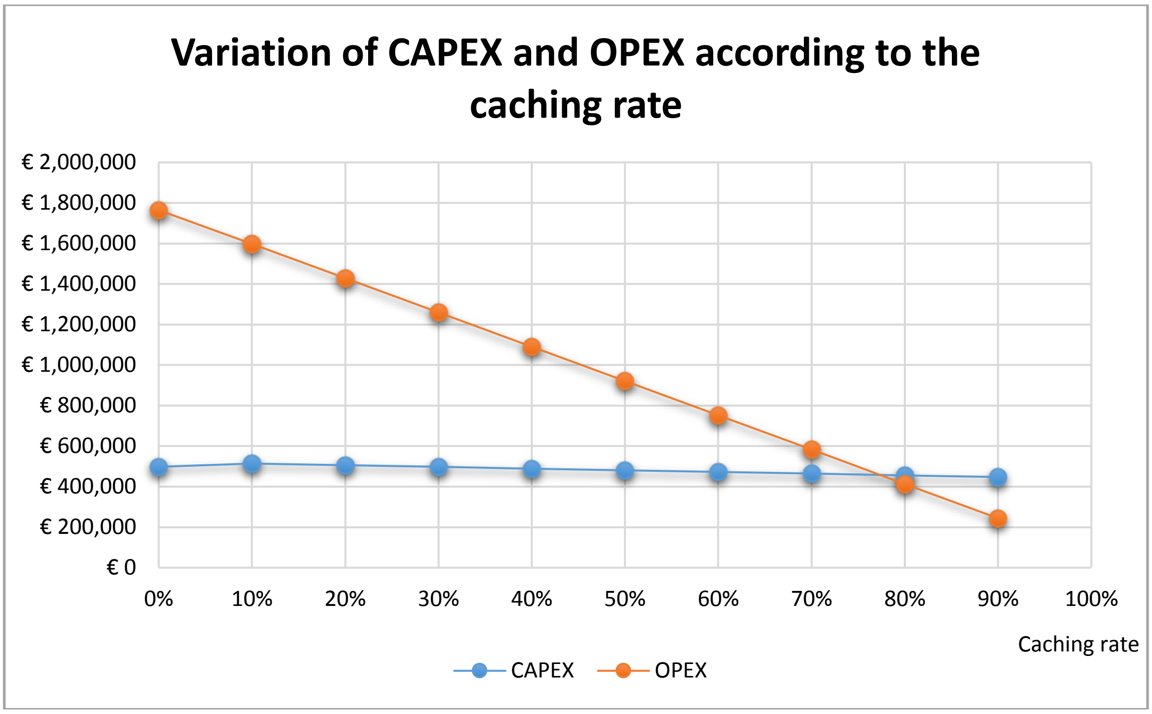

Figure 7 variation of the CAPEX and OPEX for the aggressive scenario in function of the variation of the caching rate

Several interpretations can be extracted from the Figure 7 related to CAPEX and OPEX. On the one hand, the CAPEX increases with the use of caching due to the cost of the MEC deployment, this can be observed in the Figure 7 at the 10% caching rate point. On the other hand, the CAPEX decreases slightly (can be seen starting from point 20%) with the increase of the caching rate due to the decrease of the traffic that needs to be sent via satellite, thus the decrease of the number of satellite terminals needed to handle the traffic. On the operational costs side (OPEX), there is a significant decrease in function of the caching rate increase. The more data is cached, the less traffic is sent via the satellite link, thus the less the satellite capacity cost is paid. One could think, based on these results, to use a high rate of caching to decrease the operational costs, however an in-depth analysis of the consumer traffic and forecasting and optimization algorithms for popular content are needed to determine the reasonable range of the caching rate as elaborated in (Cha et al., 2009).

To conclude, the main observations from the impact of varying the key inputs of the model on the outcomes are summarized in Table 7 below.

Input variable	ACPU	CAPEX	OPEX
Population density: number of users	The ACPU is very sensitive to the population density variation hence to the number of users and it is very low in dense urban areas.	The CAPEX increases with the increase of the number of users because new sites needs to be deployed to cover the need of the new users.	The OPEX increases with the increase of number of users because of the increase of the total bitrate required for the new users.
Caching rate	The ACPU decreases significantly due to the decrease of the OPEX while increasing the caching rate.	Slightly affected by the variation of caching rate.	Significantly affected by the variation of the caching rate because we save on the satellite capacity costs when we cache more data on the edge.

Table 7 Main observations of the variation of the key parameters of the cost model.

VII. SUMMARY AND FUTURE WORK

In this paper, we proposed a new broadband solution to provide the broadband connectivity to white rural areas in Europe, which is the combination of backhaul satellite communication with 4G fronthaul networks. A cost model to study the feasibility of integrating satellite communications within the 4G mobile network to bridge the broadband gap in rural Europe was proposed. Results from this techno-economic model show an Average Cost Per User (ACPU) of 12 to 155 euro, depending on the required bitrate per user, and the amount of popular content that can be cached. Therefore, for the universal broadband service (2Mbps), results prove that the proposed solution is economically viable based on the comparison of the ACPU to the WTP of the end user. In addition, the deployment of the solution without using the caching concept is not cost-effective in the case of the high data rates are required (case of aggressive scenario). However, results show that caching popular content on the edge can significantly save on OPEX costs (60%) and thus decrease the required Average Cost Per User (ACPU). Yet, the resulted ACPU of providing high-speed broadband as required by the DAE 2020 (30 Mbps) is still expensive for rural inhabitants, even with caching (66 euro for 64% caching rate and 44 euro for 80%). In addition, we proposed in this paper a sensitivity analysis to study the impact of the most important inputs of our model. Results of this sensitivity shows that indeed both the population density and the caching rate has a significant impact to a certain extend on the resulted ACPU.

Results of this modelling approach are able to give both the mobile and the satellite operators an overview of the feasibility of the proposed solution, and provide insights into the most cost-effective solution. Results for conservative and aggressive scenarios can guide operators to fix good strategies for the deployment of broadband services in rural areas in such way to guarantee both the service adoption by the rural inhabitants and to generate good revenues.

As future work, we aim to elaborate a socio cost-benefit model to be able to analyse the proposed solution on the long run from different perspectives. Furthermore, the model suggested in this paper restricts on the cost part for 5 years, our intention in the future is to expand it to a cost-benefit model for 10 years to give insights to both mobile and satellite operators about the revenues of this solution. Last but not least, the sensitivity analysis elaborated in this paper has investigated only two parameters, namely the caching data rate and the number of users. Yet still several key parameters and assumptions that should be studied carefully within this analysis, such the uptake of the service and the geographical location of the rural areas (i.e. Western Europe, Asia, Africa etc.).

ACKNOWLEDGMENT

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APPENDIX

Input	Value
Assumptions	• Area of 100 km2; • 100 km far from the nearest operator central office; • 1300 users; • price of m of fiber 50 euro; • max coverage of a macro cell is 5^2*Pi=78.5 km^2;
Price of the Fiber	5000000
Number of base stations	2
Price of base station	25000
Price of BSs	50000
Length of fiber between BSs	5000
Price of fiber to connect BSs	250000
Total price:CAPEX	5275000
ACPU/month for 5 years	67.7 euro

Figure 8 Back of the envelope calculation for the Fiber-4G solution

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